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Original article

Test Bed for Safety Assessment of New e-Navigation Systems *

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Abstract

New e-navigation strains require new technologies, new infrastructures and new organizational structures on bridge, on shore as well as in the cloud. Suitable engineering and safety/risk assessment methods facilitate these efforts. Understanding maritime transportation as a sociotechnical system allows the application of system-engineering methods. Formal, simulation based and in situ verification and validation of e-navigation technologies are important methods to obtain system safety and reliability. The modelling and simulation toolset HAGGIS provides methods for system specification and formal risk analysis. It provides a modelling framework for processes, fault trees and generic hazard specification and a physical world and maritime traffic simulation system. HAGGIS is accompanied by the physical test bed LABSKAUS which implements a physical test bed. The test bed provides reference ports and waterways in combination with an experimental Vessel Traffic Services (VTS) system and a mobile integrated bridge: This enables in situ experiments for technological evaluation, testing, ground research and demonstration. This paper describes an integrated seamless approach for developing new e-navigation technologies starting with simulation based assessment and ending in physical real world demonstrations

Keywords: Safety, eNavigation, Engineering, Test bed, Systems

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I. Introduction

Seafaring is and was always a joint undertaking between humans and their technology. Taking into account the impact of nature, such as wind, waves, etc. the dependability of technical equipment and its correct usage are essential for safe voyaging. This still holds true for the implementation of e-navigation technology.

The subcommittee on Navigation at IMO (IMO 2012) did a comprehensive gap analysis as a part of their development of a joint implementation plan for e-navigation, which is leading to an updated strategy implementation plan currently under negotiation. Regulatory safety rules like SOLAS with the International Safety Management-Code (ISM) for safety management on board or the IMO resolution MSC.252(83) for integrated navigation systems define a set of features to be implemented to guaranty safe voyage under the actual state of the art derived from formal safety assessments (see IMO MSC 85/17/1).

The new IMO implementation plan focuses on software quality and human centered design. To ensure safety of e-navigation technologies a holistic engineering approach is required**,** taking the whole sociotechnical system (man and machine) in its environment into account.

Based on this background, this paper introduces a system-oriented approach for the development of new e-navigation technologies focusing especially on safety and risk assessment. This approach is already addressed in a similar way for accident analysis (IMO decision A.849(20) and A.884(20)) and consequently it should also be applied in system analysis for new e-navigation technologies. Model driven technologies support the safety analysis during the design phase by using formal analysis methods and simulation based on a simulation framework named HAGGIS. For scientific grounding and in situ experiments, the physical test bed LABSKAUS extends the simulation environment by providing experimental Vessel Traffic Services (VTS) and Bridge Systems, reference waterways and port areas.

II. Systemic Design and Safety Assessment

Engineering e-Navigation systems requires an excellent understanding of the application domain and applied technologies. Complexity is one of the main challenges in engineering new systems due to more and more requirements, fast product life cycles, internal and external dependencies and technological constraints. Therefore, engineering applies methodologies (to define engineering activities and their order), methods and tools (to support the engineering activities) in addition to technological knowledge (Pahl et al., 2007). Engineering itself is an iterative process of synthesis and analysis activities. During synthesis, concepts and technologies are selected, applied and the product concept gets more and more elaborated: The system is ‘under design’. Engineers validate (is the system fulfilling the right requirements?) and verify (are the requirements implemented correctly?) their design. Engineers validate and verify their design as early and often as possible to reduce costs and safe time by early identification of errors and design flaws. Early trouble identification significantly reduces later costs for redesign. In electrical engineering Bell Laboratories introduced the concept of system engineering in the 1940s (Schlager, 1956). It helps to manage complexity to structure the product under development as a system with a defined system border, which consists of sub-systems, elements as atomic entities and defined relationships (like a printed circuit board with integrated circuits (micro chips) and discrete elements as capacities, resistors, transistors etc. with electric connections). With the advent of technologies to describe elements and relationship in a reusable way by using computer models, this approach became popular also in other engineering domains (Honour, 2004).

Reusable computer models of the system under design (the system model) allow continuous flow of information between the different tasks and simple implementation of the mentioned synthesis/analysis loop (Pastor et al., 2008). Paying attention to the early phases of system design (to identify and validate/verify the concepts of the product) reduce the risk of later costly design changes. The concept of frontloading aims at improving design efficiency by reusing models from the early phases in the subsequent design, validation and verification. The propagation and transformation of models along the phases of the design process is called 'model driven design'.

The process of developing new systems starts with the analysis of processes for using existing systems to identify existing hazards. Starting with the requirements engineers drive a functional specification of the new system (Sangiovanni-Vincentelli et al., 2012). Engineers use a functional modelling language to describe the functionality of the system. It is the modelling language that defined the exact semantic for an executable model. This executable functional model is a basis for early testing and safety assessment: By using a model execution engine the functional model of the new system can run as a system in a simulated environment (software in the loop). The simulator generates input from sensor systems and input from communication to other systems. Software components named user agents simulate user behaviour. The agents interact with the functional model by a virtual user interface. The virtual user interface is a computer internal representation of the user interface.

Actually and especially dedicated engineering domains like embedded systems design use elaborated test environments for Model In the Loop, Software in the Loop, Hardware in the Loop, Human in the Loop and Physics in the Loop (MIL, SIL, HIL und PIL) testing. In the automotive industry, preconfigured test beds are available (Kuppusamy et al., 2011). There are even approaches in the maritime sector especially in shipbuilding (DNV, 2011).

In Figure 1 a scenario is sketched for testing user interaction of an assistance system (e.g. an autopilot) for an integrated bridge system. The functional model defines the functionality of the system as specified by the engineer. Execution can be done e.g. by MasCAS, which is introduced in chapter 4.2. Simulation agents are used to simulate user behaviour. The agents implement cognitive models and these models are executed by using a software component named CasCAS (s. also chapter 4.2). The CasCAS-controlled agents interact with the assistance system using a virtual interface implemented as a virtual bridge. The user agents use the virtual user interface in the same way a human would use the real physical user interface. For testing, a maritime traffic simulator generates the required test cases.

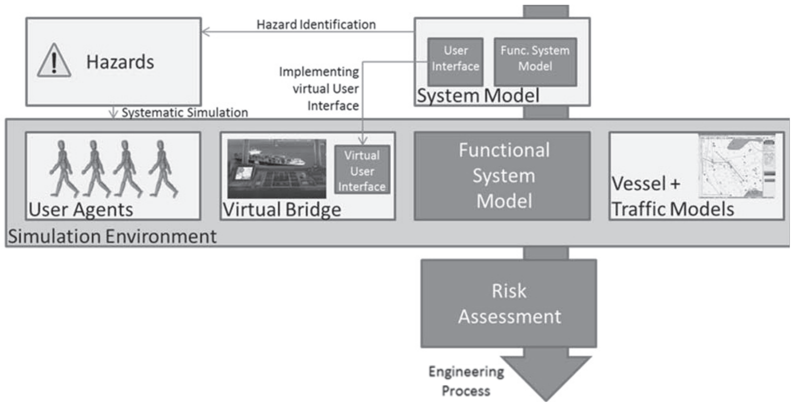

Figure 1: Simulation based Risk Assessment

The focus while testing the new systems in the virtual environment is on safety assessment and hazard detection. The identified hazards are used by the simulation environment to systematically seek risky/hazardous situations using rare event simulation techniques (Bucklew, 2003). The behaviour of the system is protocolled for further consideration in the engineering process.

After successful assessment in the virtual environment and subsequent analysis and synthesis iterations for improvement, the prototype of the assistance system then can be assessed in a physical test bed. The prototype can be a virtual as the functional model or already a first physical implementation. The architecture described in Section 3 allows for direct deployment of the software systems on physical test platforms without adaptation to the new platform. This transparent usage of platforms is known from other platforms like Player(Gerkey et al., 2001), ROS(Quigley et al., 2009) or DOMINION(Gacnik et al., 2008) in the robotics and automotive domain. Changing the test environment to the physical platform is done by deploying the software on an experimental VTS or a mobile bridge for example. The virtual user interface will be substituted by the real user interface and test persons will perform the actions that have been simulated by the user agents.

III. A platform for seamless development of e-navigation technologies

One of the main challenges in the design and development of new e-navigation technologies is the test environment. e-Navigation technologies are used in a rough environment (on sea), in which real world testing is not always possible. Therefore, simulation-based testing of new concepts is necessary and therefore a very detailed and realistic simulation platform has to be used. However, still a gap between simulation and real world will remain. To reduce this gap, we developed a model based approach for design and development of new e-navigation technologies based on a seamless architecture covering simulation and real world assessment that is shown in Figure 2.

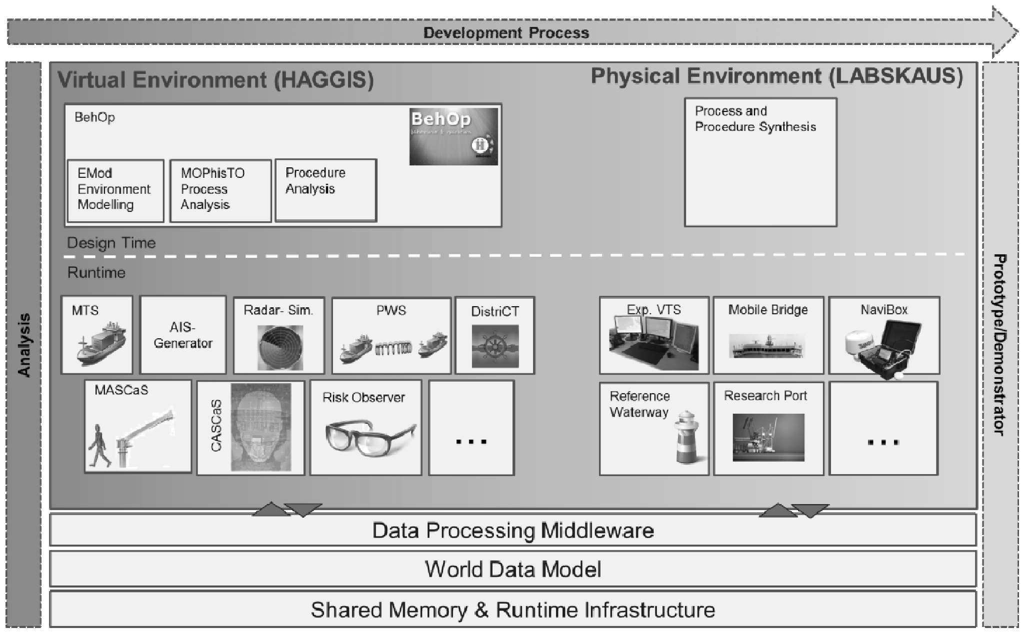

Figure 2: Architecture for seamless testing of new e-navigation technologies

This architecture allows the early testing of new e-navigation technologies in a complex simulation environment and the seamless transfer of these technologies into a physical testbed. The basis of the architecture is a shared memory and runtime infrastructure, a common world data model and data processing middleware.

The shared memory & runtime infrastructure currently is a modified high level architecture implementation. This infrastructure allows the communication between different simulation components in a co-simulation environment but also the communication with developed software and physical testbed systems.

The world data model is the common semantic basis for all intelligence implemented in the simulation and the newly developed e-navigation technologies. It takes into account IHO S-100 aspects and is the virtual representation of the physical world. All simulation components as well as physical components like the mobile bridge work use this data model to generate high value semantically enriched information. The data processing middleware transforms data from different formats like NMEA 0183 and 2000, Asterix, IVEF etc. into the world data model. Furthermore, it is easy to extend the sensor fusion middleware for generating high value information depending on what is necessary for the e-navigation technology under development.

This architecture supports the development of completely new e-navigation technologies like assistance systems for vessel guidance. Support is given from the analysis phase until the development of prototypes and demonstrators. The improvement to product quality level is done later phases of the development process.

The platform can be used to derive models to understand the environment, the role of humans and its interaction with the developed technology. The main purpose of the platform is to ensure functional safety.

IV. Simulation Environment

System engineering shows that models are well suited to support the engineering process and to provide a valuable basis for validation and verification of the system under development e.g. for safety assessment.

This can be done formally by analyzing the model of the system and informally by using simulation tools. It requires that the models are sufficiently formal and executable. In addition, the test environment has to be defined (modelled) as well. Therefore, we split the simulation environment HAGGIS in a modelling and formal analysis toolset and a co-simulation environment.

4.1. Modelling and Formal Analysis

Figure 3 shows the general approach for modelling and formal analysis. For the safety analysis of new e-navigation systems (e.g. like a new integrated navigation system on bridges) a ground research is done by analysing guidelines, accidents reports, nautical manoeuvers etc. We use a generic hazard list to identify potential harming issues in the system. Process models are used to describe the activities (e.g. operations) and they are enriched by defining information availability, requirements and generic hazards. Formal model checking technology can be applied to analyse, if bridge systems allow the required situation awareness of the crew. Further, automatically generated fault trees serve as a tool to identify and quantify the potential risks.

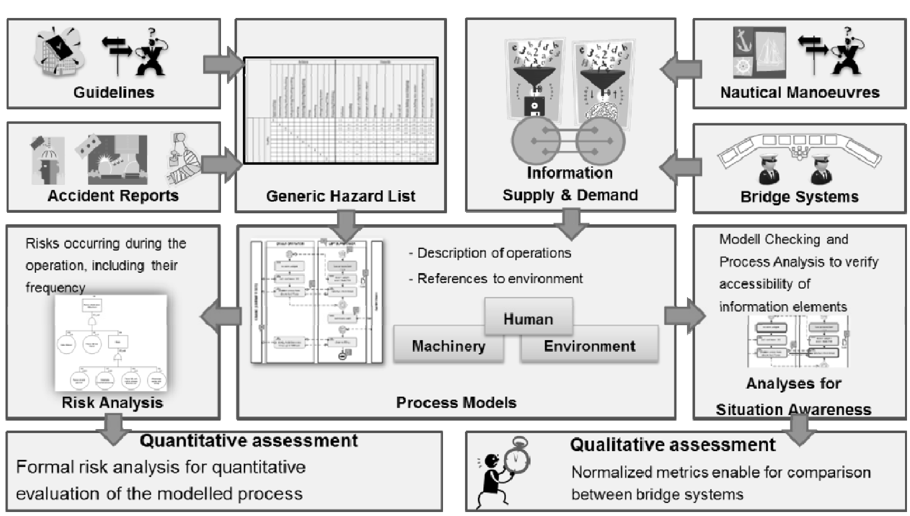

Figure 3: Modelling and Analysis Process

The analysis results in quantitative or qualitative risks / safety assessments. To support the assessments, a number of tools are available: MOPhisTO – Maritime Operation Planning TOol, ShiATSU - Analysis of Situation Awareness on Ship Bridges and FTA – Fault Tree Analysis. This toolset is accompanied by EMod – Environment MODelling tool for defining the system environment for analysis by simulations. An overview about the interactions of these tools is given in Figure 4.

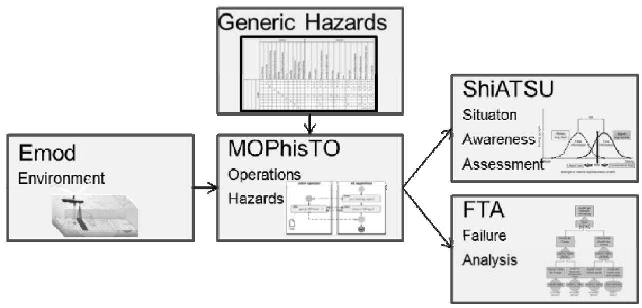

Figure 4: Modelling and Formal Assessment Tools

4.1.1. EMOD – Environment MODelling

EMod is an Eclipse-based editor that provides a system model to allow setting up a static scene according to a predefined scenario. This system model contains the fundamental components/entities of all used resources, actors and environmental factors. The user is able to load 3D geometric models of e.g. ships. The properties of these objects can be set according to the user´s need.

4.1.2. MOPhisTO – Maritime Operation Planning TOol

MOPhisTo enables maritime domain experts to graphically model processes of the operations defined for their field of expertise (Droste et al., 2012). The process models are enriched by linking them to required information supply and demand as well as hazards from the generic hazard list. This information is used for information gap and automatic risk analysis. Additional benefit of the models is the option to use them for training and documentation purposes. MOPhisTo can make references to the data modelled with EMOD. MOPhisTo supports the description of normative behaviour for maritime personnel (e.g. individual tasks of an officer) and maritime machinery (e.g. behaviour of an adaptive display). The process modelling language is based on BPEL (Ouyang et al., 2007). BPEL is extended to express the required references to EMOD entities like failures etc.

4.1.3. ShiATSU – Situation Awareness Tool SUite for Ship Bridges

ShiATSU is a tool suite for analysis of situation awareness on ship bridges during design time. It allows for analysis of socio-technical ship bridge system setups consisting of a ship bridge, operators and organizational aspects. Operators' interactions with information elements are extracted from MOPhisTO's normative processes and considered as information flows between human operators and the ship bridge. An automatic analysis is used to assess the information flows by facilitating multi-dimensional (e. g. consisting of 3D-space, time, information quality, …) models of the ship bridge. The analysis comprises a verification of information accessibility, measurements of the spatio-temporal information access and supports engineers by identifying causes for situation awareness errors by consideration of distributed situation awareness. The measurement results in normalized metrics, which allow for system optimization and comparison.

4.1.4. FTA – Fault Tree Analysis

MOPhisTO is used for formal description of normative processes and the annotation of hazards and failures. The integrated FTA tool performs an automatic fault tree construction by using the modelled hazards and failures (Lee et al., 1985). Resulting fault trees are the basis for a formal quantitative and qualitative risk assessment.

The tool enables a graphical presentation of generated fault trees to the user as well as manual construction of fault trees. Additionally, they are used for automatic generation of textual risk assessment results e.g. to construct Health Safety and Environment (HSE) plans (Sobiech et al., 2012).

Since identification of hazards and failures is important in early project phases, the tool supports users by suggesting hazards and failures modelled in the past. Therefore, it comes with a formal approach to learn from performed analysed data that can later be reused to model hazard/failure combinations.

4.2. Co-simulation Environment

The sociotechnical model is analyzed in a simulation environment. The process models and the environment models are used to describe the system under analysis. The Generic Hazard List and the process models are used to define the normative behaviour and provide a basis to identify critical situations during simulation. For human behaviour a cognitive simulation is used. The approach is shown in Figure 5 and the general architecture of the co-simulation is sketched in Figure 6. Inputs are normative behavior and environment models. A maritime traffic simulator and a n-body simulator provide the required environment of the e-navigation experiments.

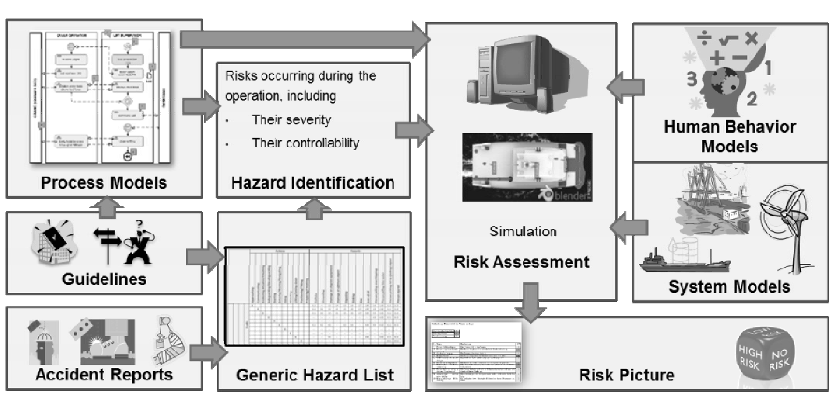

Figure 5: Simulation Based Risk Assessment

Agents are brought to live by MASCAS. MASCAS executes the defined behaviour. CASCAS is a cognitive simulation that implements the real human behaviour by performing designated tasks (Lenk et al., 2012). The implementation currently uses a modified High Level Architecture (HLA) as a co-simulation architecture with data specification of the world data model in HLA specific object model template (OMT) files. HLA is defined under IEEE Standard 1516. OMT provides a common framework for the communication between HLA simulations. Standardized wrappers are used to speed up the simulator integration. All data exchanged by the simulators is defined by the semantic world data model. A simulation control tool runs simulations automatically and supports the detection and provocation of rare events in combination with observer components for observing the simulation. The observer components are automatically generated by using the models defined with MOPhisTo.

4.2.1. MTS - Maritime Traffic Simulator

The MTS is a flexible usable maritime traffic simulation for implementing, executing and observing the behaviour of multiple vessels in a realistic context. Each of these vessels has a dynamic model that describes its behaviour regarding environmental influences, like waves, current and wind. In addition, each vessel is steered by an intelligent agent to follow a predefined path or find its own path according to the maritime law regulations. The MTS is used to provide all necessary data about the traffic situation that is required by statical analysis or other simulators.

4.2.2. N-Body simulator

The N-Body simulator simulates the physical interactions of rigid bodies inside the simulated environment (Schweigert et al., 2012). That could be: The displacement of the cargo due to a collision with another object or the rapid (heave/sway/surge) movement. It contains a collision detection capability that allows for checking constraints like man under cargo or man overboard.

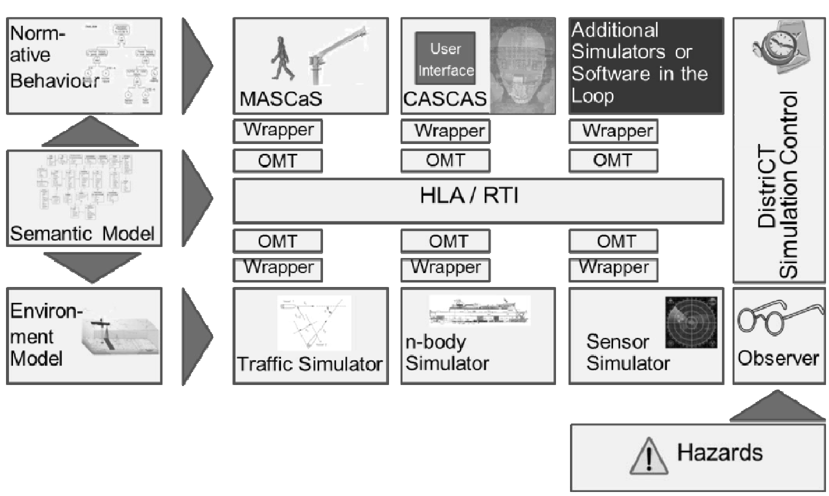

Figure 6 : HAGGIS Co-simulation Environment

4.2.3. Sensor Simulation

The sensor simulation is used to generate realistic sensor measurements from a simulated context, e.g. the context of the maritime traffic simulation. The generated measurements can be extended by statistical, systematic or context-sensitive error models. In combination with a traffic simulation the Sensor Simulation generates AIS-targets or radar-targets and radar images.

4.2.4. MASCaS

In order to simulate simplified agents models by MOPhistTO, a simple model interpreter (MASCaS) has been implemented in Java. Changes of agent states are communicated via HLA to their related avatars in the N-Body simulation or Maritime Traffic Simulation. For example, MASCaS can give the avatar a motion command that is implemented by a description of the behavior of the avatar or the movement is directly controlled by the agent.

4.2.5. CASCaS (Cognitive Architecture for Safety Critical Task Simulation)

The cognitive architecture CASCaS is used to model human behaviour. CASCaS models generic domain independent cognitive processes in a modular way taking into account human perception, memory, knowledge processing and motor skills (Lenk et al., 2012). A key concept underlying CASaS is the theory of behaviour levels which distinguishes tasks with regard to their demands on attentional control that is dependent on prior experience: autonomous behaviour (acting without thinking in daily operations), associative behaviour (selecting stored plans in familiar situations), and cognitive behaviour (coming up with new plans in unfamiliar situations).

4.2.6. DistriCT (Distributed Controlling Toolkit)

DistriCT can be used to set up and control simulation components on different distributed systems. This involves starting and stopping of simulation components as well as receiving and sending objects to them. This can be used to inject failures or perform a systematical parameter exploration. Observers are used to evaluate the system state and the logical or physical distance to hazardous situations. They identify minima in these distances and guide the simulation in the direction of critical situations to find rare events and to reduce the required number of simulation runs.

4.3. Implementation

HAGGIS implements a co-simulation scenario, which combines multiple independent simulators to a joint simulation. The co-simulation in controlled by DistriCT as described above. All simulators have to simulate a consistent and partly shared model of the "world". E. g. avatars of MASCAS controlled agents are acting in an environment simulated by MTS or the n-Body Simulator.

Technically the cooperating simulators have to synchronize the models and timing in the simulation. In our case, this is technically achieved by using a High Level Architecture (HLA) compliant implementation (Nouland et al., 2009) like described in [is this sentence complete?

“like described in” where?] (Läsche et al., 2013). To ensure interoperability of the co-simulators the data is exchange by using a common semantic data model that incorporates the concepts of S-100 standard.

V. Physical Testbed

The virtual environment is accompanied by the physical environment and testbed LABSKAUS (laboratory for safety critical experiments at sea). LABSKAUS is a living lab for experiments and traffic surveillance and provides a grounding for the HAGGIS simulation experiments and itself is based on the same world data model and the same architecture as HAGGIS. LABSKAUS offers services for e-navigation experiments. Services are a reference waterway, a research port, a mobile bridge system and a Vessel Traffic Services (VTS) System. One generic element for its implementation is the Navibox for mobile sensor systems.

There are actually around 15 test beds for e-navigation technologies under development. Most of them are installations of single technologies under development. LABSKAUS is an open infrastructure that provides generic services, flexible setup of test environments and interfaces for integration with test beds.

5.1. Reference Waterway

The Reference Waterway covers the Elbe and Kiel Canal Approach near Brunsbüttel, Germany. It covers a basic maritime surveillance infrastructure with three Naviboxes (including AIS, Radar, cameras) and broad band communication via satellite and LTE. The system is used as an experimental platform and for demonstration of new technologies as well for setting up a database with travel patterns and near collisions. The objective for such a reference waterway (more areas are in progress) is to have a completely electronically covered area, with communication technology available for data exchange and with surveillance technology available for information gathering. Using such a reference waterway will allow us the testing of new vessel assistance systems based on newest information technology available. The following Figure shows a sketch of the reference waterway idea.

5.2. Research Port

The research port addresses experiments for sensor data fusion in port areas. The small port Gestemündung in Bremerhaven, Germany has a ferry terminal, berths and an entry to a popular double lock. The research port is equipped with a mobile sensor network of NaviBoxes (see section 5.5) especially to experiment with optical systems (visual light, IR and UV) in cameras and laser systems. The NaviBoxes set up an ad hoc sensor network with broadband communication.

Figure 7: SensorBox

5.3. Mobile Bridge

For bridge experiments in lab and on ship a mobile bridge system allows set up of an experimental bridge on board without interfering with the vessels navigation systems. It provides a Raytheon Integrated Bridge in its standard configuration (other software is optional) and is linked to a Navibox which provides required navigational data such as compass, GPS, AIS, log, lot, radar, as well as a broad band communication system. This mobile bridge is used for experiments with assistance systems and for human centered design analysis.

Its mobile design consists of a controlling unit, modularly mounted with a PC station. The controlling unit enables ship steering e.g. put the rudder (in areas where permissions are given for this). The PC works as Electronic Chart and Data Information Systems (ECDIS) and radar display that is common on ship bridge systems. The overall mobile bridge system is transportable within a box including display components, and ready-to-use for experimental applications with or without external power supply.

From the software perspective it is possible to connect simulation environments to the mobile bridge e.g. to send simulated sensor data. Intelligence from new developed e-navigation assistance systems is based on the world data model. E. g. collision detections uses the already mentioned world data model for analyses of the current traffic situation and for generating adequate alarms.

5.4. VTS system

An experimental VTS system was implemented by the company Signalis at the maritime research center in Elsfleth. It can be linked to the Reference Waterway and the Research Port as well as to the virtual environment HAGGIS. It consists of a PC system and multitouch display components, which are used for HMI research applications in order to improve the current state-of-the-art designs.

5.5. Navibox

The Navibox is a mobile, connectable sensor data hub which provides navigational data on board as well data for maritime surveillance systems. Sensors can be configured ad libitum. The Navibox provides WLAN and Broadband WAN communication facilities. The box is a robust outdoor box and comes with a radar pole, compass and GPS. At the moment the NaviBox is in use for traffic data recording in the river Weser as well as the entry to Kiel Canal in Brunsbüttel. In a second configuration the NaviBox is equipped with optical surveillance technologies like a visual camera, infrared and ultraviolet camera. As mentioned in section 5.2 these sensors are currently used in a research port for tracking water vehicles, but in future the optical systems will be used for near-field target tracking of vessels in port areas and dense fairways.

Figure 8: SensorBox

5.6. Implementation

LABSKAUS is an open service oriented framework. It provides flexible services to set up experiments for verification and validation of technologies. Core is a configurable message passing system to connect the technologies mentioned above. It is extended by services for sensor data fusion, persistent storage etc. Both HAGGIS and LABKAUS have generic data model to ensure interoperability of the components and a configurable interface component which provides standard interfaces (like NMEA).

VI. eMIR - eMaritime Reference Platform

LABSKAUS and HAGGIS are part of the open eMaritime Reference Platform a lead project and demonstration system of the German working group for civil maritime safety to implement the strategic national master plan in maritime technologies. In addition to the presented simulation system and physical test bed, eMIR covers also the Research Port at Rostock for experiments with satellite technologies and resilient Position Navigation and Timing (PNT).

eMIR is an initiative of the german maritime industry. The services are developed and driven by industrial partners from the eNavigation domain (bridge systems, surveillance systems etc). Each service has already used these partners and eMIR offers the cross usage of these services. eMIR supports existing industry demands).

VII. Conclusions

Safety and dependability are the design goals of e-navigation systems. Model driven technologies support the efficiency of the development process and enable early design assessments, especially safety requirement verification and validation. To support a system engineering approach for e-navigation systems the paper introduced the eMaritime Reference Platform eMIR with a virtual simulation based environment (HAGGIS) and physical environment and test bed (LABSKAUS). HAGGIS supports modelling and formal analysis of e-navigation systems and a co-simulation environment with traffic and n-body simulation systems as well as human agent models for human centered design engineering. LABSKAUS provides an experimental VTS System, a mobile ship bridge and a reference port and a reference waterway for e-navigation experiments and systems demonstration. Both are based on a common architecture and data model to allow for a seamless development of new e-navigation technologies.

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